A HOUSE GENERATION-LOAD MODEL

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by

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[To the students of the Georgia Institute of Technology]

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LIST OF ABBREVIATIONS

AC	Air Conditioner
BESS	Battery Energy Storage System
DLC	Direct Load Control
DOD	Depth of Discharge
DOE	Department of Energy
DR	Demand Response
DSM	Demand Side Management
EERE	Office of Energy Efficiency & Renewable Energy
EIA	Energy Information Administration
FERC	Federal Energy Regulatory Commission
ISO	Independent Service Operator
PV	Photovoltaic
SOC	State of Charge
TOU	Time-of-Use

SUMMARY

Time-of-Use (TOU) pricing plans put in place by utility providers create an opportunity for homeowners to reduce their electric bill by shifting demand to off-peak hours and/or lowering their peak-demand. This is accomplished by offering incentives in the form of lower electric rates at different times, or by charging the customer partly based on their peak kW demand. Existing battery energy storage system (BESS) technologies provide an opportunity for the homeowner to increase these benefits by discharging the BESS to reduce peak loads or to reduce loads during on-peak hours that otherwise could not be shifted to off-peak times.

Batteries have had their operation extensively studied, providing a solid foundation for use in distribution level simulation. These studies provide information and physical models for batteries varying by chemical composition and size, and allow for easy integration with other physical models. This research presents the project valuations of several different BESS installation options for a homeowner.

The purpose of this thesis is to quantify the benefits to a homeowner from the use of batteries in the presence of time of day electricity pricing. For this purpose, a physical model of a typical residence, two BESS, and a distribution network are developed to determine a daily load profile for this residence, and the impact two BESS have on this demand. An economic model is developed to provide the present value of installing these systems based on TOU pricing plans. Simulating the physical and economic models provides the expected difference in energy consumption between different BESS options

and the expected value of each, resulting in a quantified cost benefit estimation for a homeowner considering installing a BESS.

CHAPTER 1

INTRODUCTION

High Penetration of renewable energy generation and rapid changes in electric generation and demand creates challenges for a power system. These changes can be mitigated with the addition of demand response (DR) programs on the utility and the distribution level. These DR programs provide stability for the power gird as well as economic benefits to both the utility providers and end use customers.

The current electric power grid is divided into power generation, high voltage transmission to substations, and distribution to customers. There are concerns for the stability, affordability, security, and environmental impact of the grid [1]. Many of the stability and security concerns can be mitigated with energy management DR programs, while both utility and customer controlled DR programs can mitigate affordability and environmental concerns.

Many of these DR programs involve the use of BESS. Demand side BESS can help customers with load shifting, which can reduce their peak consumption, and integrating residential photovoltaic (PV) cells, both providing an economic benefit. Utility owned and controlled BESS can allow power system operators to expand emergency backup power, reduce the use of old or expensive generators through peak shaving and load shifting, regulate frequency, and integrate large scale renewable resources [2].

This thesis develops a computer based model for a typical house and a residential sized BESS. Using these models, the apparent daily load profile of a typical house, with and without a BESS installed can be determined. With this information the kWh power consumption of the house can be determined and used to compare the cost of electricity varying by TOU price rates. This method forms the basis for the project valuation of adding a residential BESS.

The rest of the thesis is as follows. Chapter 2 reviews recent literature concerning these topics and the current state of DR and BESS technologies. Chapter 3 details the setup of the load profile for a typical residence via the loads within, the model of two separate residential BESS, and the distribution network serving this residence. Chapter 4 details the economic model for finding the present value of installing a BESS based on TOU prices. Chapter 5 presents the results of each simulation in the form of daily load profiles and total lifetime cost valuations. Chapter 6 summarizes the results.

CHAPTER 2

LITERATURE REVIEW

There has been much research and focus on DR programs both for demand side management (DSM) and energy management over the past several decades. A vital component of both uses for DR are BESS. This chapter provides a review of existing literature and research on both DR programs and the use of BESS in these programs as well as a brief synopsis of BESS technologies and modeling techniques.

2.1 Call for Demand Response

The ability to respond to sudden changes in electricity demand and prices has become increasing important in recent years. DR programs used to temporarily decrease demand for power have proven valuable in helping maintain generation-load balance while providing financial benefits to customers. DR programs are especially useful in reducing peak loads and integrating renewable energy sources [3], [4]. These programs function as DSM for utility providers by allowing them to reduce the electric demand rather than only being able to change electric generation.

Direct load control (DLC) DR programs involves power system operators having control over customer loads, allowing them to turn larger loads, such as heating/cooling or water heaters, on or off. These programs are most often used during peak demand times and emergencies [5]. Reductions in demand can also be customer controlled, where the customer is incentivized to reduce their demand during peak hours [6]. Customer controlled DR programs typically use TOU pricing which varies the price of electricity depending on the time of day. These pricing plans encourage customers to shift to provide benefits to the customer while optimizing power system operation [7].

These load control programs have a significant impact on both the price of electricity and stability of the power grid, and have been adopted by many independent service operators (ISO) [8]. This has resulted in the U.S. Department of Energy (DOE) and the Federal Energy Regulatory Commission (FERC) studying and promoting the use of DR programs for both private and public uses [9]. Additionally, the DOE has identified DR and energy storage as sources of value in operation of the power grid and integration of renewable resources [3].

2.2 Battery Energy Storage Systems

BESS are an important part of grid level energy management and DR. These battery technologies provide a wide range of applications, including renewable resource integrations, peak shaving, load shifting, energy storage, and power quality management. While pumped hydro and compressed air energy storage make up the vast majority of currently installed electrical energy storage, they are mostly used for bulk power storage and are restricted in where they may be located [2]. BESS have an advantage of being modular, and may be used in smaller scale applications and energy management.

For renewable energy integration, BESS have shown to be a capable and cost effective method of load shifting in conjunction with PV cells in residential applications [4], [10]. These provide a financial benefit to the residential customer, and given the wide range of BESS capacities this benefit can be further maximized. In addition to working in conjunction with PV cells and other renewable resources, BESS have proven beneficial by themselves in terms of reserve supply and peak clipping DR on the demand side [11]. Energy storage has also been implemented on the utility side, showing economic benefit when used for spinning reserve, load leveling, and frequency control by the power system operators [12].

There are currently a variety of different BESS technologies that range in maturity from demonstration and laboratory testing to proven commercially developed [2]. Some of the more usual types are Lead-Acid, Lithium ion, and Sodium-Sulfur. Each of these technologies are better suited to different applications based on their design and construction. Lead-Acid batteries are widely used due to their low cost, but most often used for emergency power backup due to their lower operation life. Lithium ion batteries are often used for consumer devices as they have lower weight and size and are capable of being fully discharged, but are often more expensive than other batteries. Sodium-Sulfur batteries are often used in utility size systems for energy management [2].

Several different equivalent circuit models for batteries have been developed in order to incorporate BESS into computer simulations [13]. The simplest of these models is the Ideal Model, where the battery is shown as a voltage source, ignoring internal parameters. The Linear Model adds an internal resistance to the Ideal Model, and the Thevenin Model expands on the Linear Model by also adding overvoltage impedance. Each of these models can be further improved by having the internal parameters dependent of the battery state of charge (SOC) [13].

CHAPTER 3

COMPONENT AND SYSTEM MODELS

In order to simulate the power draw of a typical residence and a BESS a computer model was developed for both a house and a BESS, along with a distribution level test system. The methodology for developing the models for both a residence and a BESS are shown in sections 3.1 and 3.2 respectively, and the methodology for the test system is shown in section 3.3.

3.1 House Component Models

An individual house can be represented by each component load within the house. In order to represent a typical residence, the loads of seven household appliance and various loads used to simulate lighting and wall outlets were used to approximate the daily power demand of the house.

3.1.1 Air Conditioner Model

A central air conditioner (AC) unit can be modeled as a load of active and reactive power cycling on and off throughout the day in order to provide cooling to the house. Typical voltage for a central AC unit is 240 V, and uses a line to line connection. A central AC unit will also have a fan supplied by a separate circuit that is offset from the AC on cycles by approximately 30 seconds [14]. This fan operates at 120 V using a line to neutral connection.

Pipattanasomporn et al [14] measured the power consumption of a central AC unit over a 12-hour period, from 10:00 am – 10:00 pm, thus this load profile was used for those hours. Since AC units operate less frequently at night due to decreased use, the number of load peaks were reduced during the hours of 10:00 pm – 10:00 am. These loads are shown in Figure 3.1. Note that this does not include the fan supplied by a separate circuit.

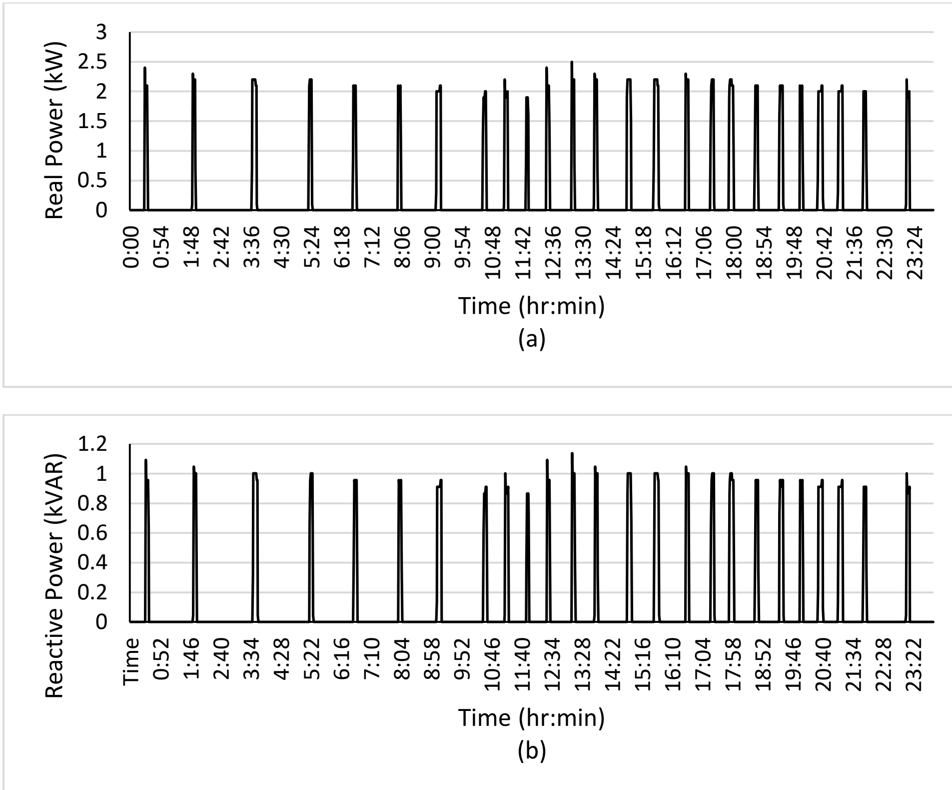


Figure 3.1. Air conditioner load profile: (a) real power; (b) reactive power.

3.1.2 Water Heater Model

An electric water heater can be modeled as a load of active power operating at approximately unity power factor at various times throughout the day. Typical voltage for an electric water heater is 240 V, and uses a line to line connection. The water heater operates at several different occasions: when showers are in use, when sinks or the dishwasher are in use, when the washing machine is in use, and when necessary to maintain water temperature in the tank [14].

The water heater was assumed to operate in the morning and evening to provide hot water for showers, sinks, and appliances. It also operated in the afternoon in order to maintain water temperature. These loads are shown in Figure 3.2.

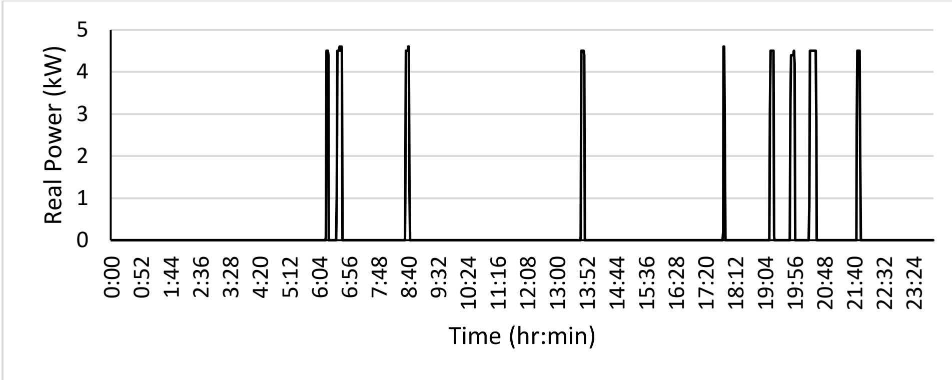


Figure 3.2. Water heater load profile: real power.

3.1.3 Clothes Washer Model

A washing machine can be modeled as a load of active and reactive power operating when the appliance is in use. A typical washer in a stacked washer/dryer unit can operate at either 120 V or 240 V single phase, using either a line to neutral or line to line connection respectively. Washing machines have several settings of operation including normal, permanent press, and delicates. Depending on the model there may be additional settings such as quick rinse, spin only, and settings for specific fabrics. Each setting will cause the washing machine to run at a different load and power factor [14].

For this model the washing machine operates at 120 V, and its run starts at 8:00 pm and lasts for an hour. It is assumed to be operating on the normal setting. This load is shown in Figure 3.3.

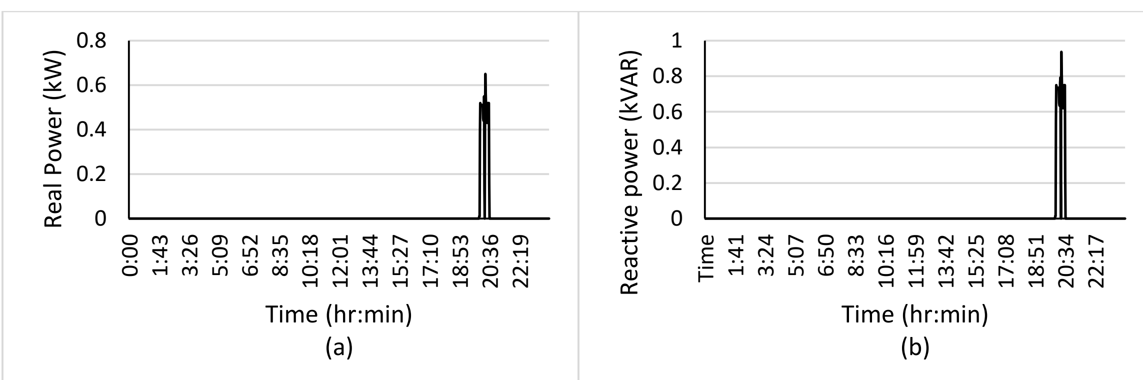


Figure 3.3 Clothes washer load profile: (a) real power; (b) reactive power.

3.1.4 Clothes Dryer Model

An electric dryer can be modeled as a load of active and reactive power operating when the appliance is in use. A typical electric dryer in a stacked washer/dryer unit can operate at either 120 V or 240 V single phase, using either a line to neutral or line to line connection respectively. Electric dryers operate either on a manufacturer created setting for specific materials; i.e. cottons, delicates, etc.; or on a timed dry setting, where the user manual sets how long the dryer is in operation for. During operation electric dryers will start by using heating coils to raise the temperature in the dryer. Afterwards the dryer will alternate between an unheated tumble and a tumble with the heating coil in operation [14].

For this model the electric dryer operates at 240 V single phase, and its run starts at 9:00 pm and lasts for an hour. It is assumed to be operating on the auto-regular setting. This load is shown in Figure 3.4.

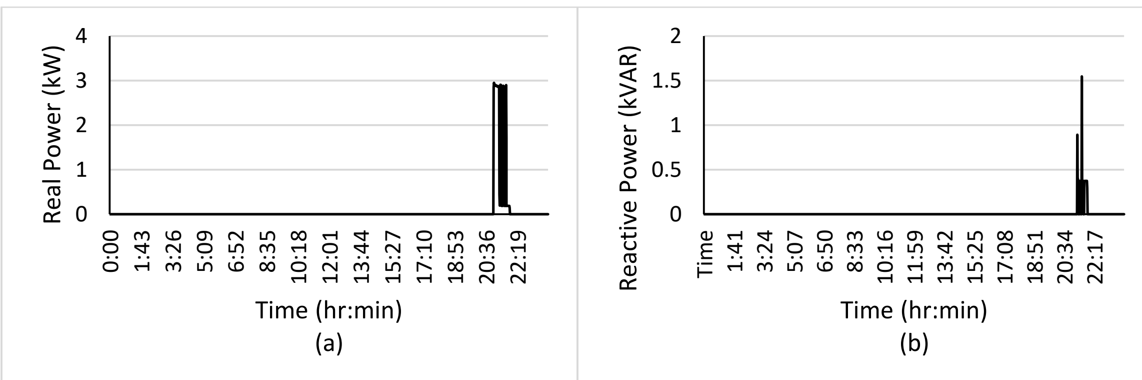


Figure 3.4. Clothes dryer load profile: (a) real power; (b) reactive power.

3.1.5 Dishwasher Model

A dishwasher can be modeled as a load of active and reactive power operating when the appliance is in use. Typical voltage for a dishwasher is 120 V, and uses a line to neutral connection. There are four cycles of operation for a dishwasher; prewash, wash, rinse, and dry. During the wash, rinse, and dry cycles the dishwasher will operate both with and without the heating coil active, with the coil initial active in order to raise the temperature of the water, and then inactive in order to reduce electricity consumption [14].

The dishwasher was assumed to operate after dinner at 8:30 pm, and runs for 90 minutes. This load is shown in Figure 3.5.

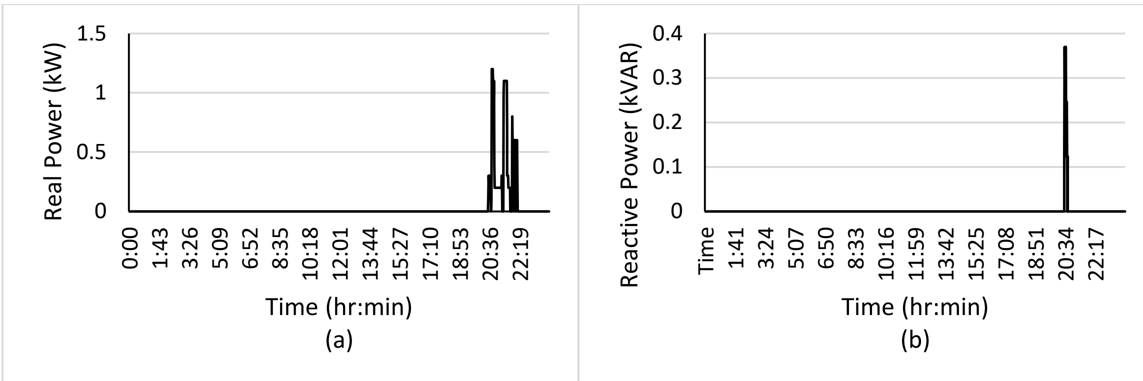


Figure 3.5. Dishwasher load profile: (a) real power; (b) reactive power.

3.1.6 Refrigerator Model

A refrigerator can be modeled as a load of active and reactive power, cycling on and off throughout the day in order to maintain temperature within the appliance. Typical voltage for a refrigerator is 120 V, and uses a line to neutral connection. Additional peaks in power consumption occur both when the door is opened, due to the inside light bulb and the fact this prolongs the on cycle, and during a defrost cycle, which lasts approximately 20 minutes [14].

Pipattanasomporn et al [14] measured the power consumption of a refrigerator at two different time periods; from 1:00 am to 5:00 am in order to capture a time period where there was little activity and the door was not opened, and from 8:00pm to midnight in order to capture a time period where there was activity and a defrost cycle.

To represent a refrigerator's operation through an entire day, the early morning load profile was assumed to mirror times when there would be little activity and the evening load profile was assumed to mirror times when the refrigerator would be in use. The early morning load profile was used from midnight – 8:00 am and noon – 4:00 pm, and the evening load profile was used from 8:00 am – noon and 4:00 pm – midnight. However, the defrost load was only used once in the evening as a typical defrost cycle will only happen every 30 – 40 hours [14]. These loads are shown in Figure 3.6.

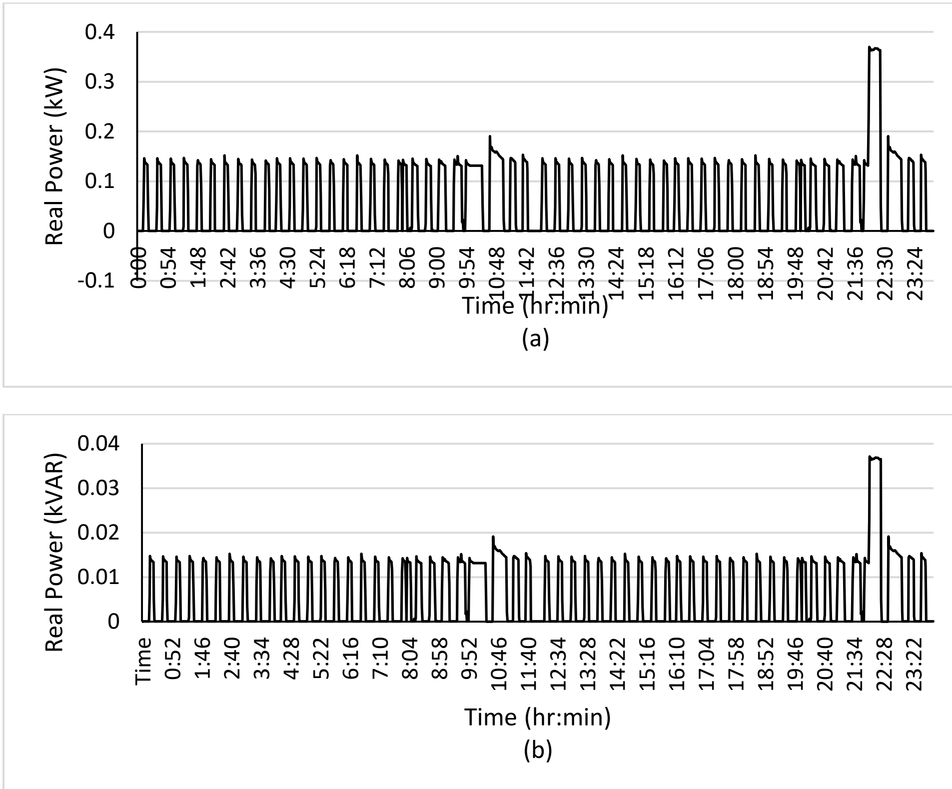


Figure 3.6. Refrigerator load profile: (a) real power; (b) reactive power.

3.1.7 Oven Model

An electric oven can be modeled as a collection of smaller loads, one for each heating element. There are two small cooktop burners, two large cooktop burners, and an oven which can either be set to a bake or a broil setting [14]. Each of these heating elements can be modeled with a load of active and reactive power when in use. Typical voltage for an electric oven is 240 V, and uses a line to line connection.

To represent an electric oven's operation over the course of a day, it was assumed to be in use for breakfast from 8:00 am – 8:30 am, and for dinner from 6:30 pm – 7:30 pm. During breakfast both a small and a large cooktop burner were assumed to be in use, both for 30 minutes. For dinner a small and large cooktop were assumed to be in use for

30 minutes each in addition to the oven being set to bake for 1 hour. These loads are shown in Figure 3.7.

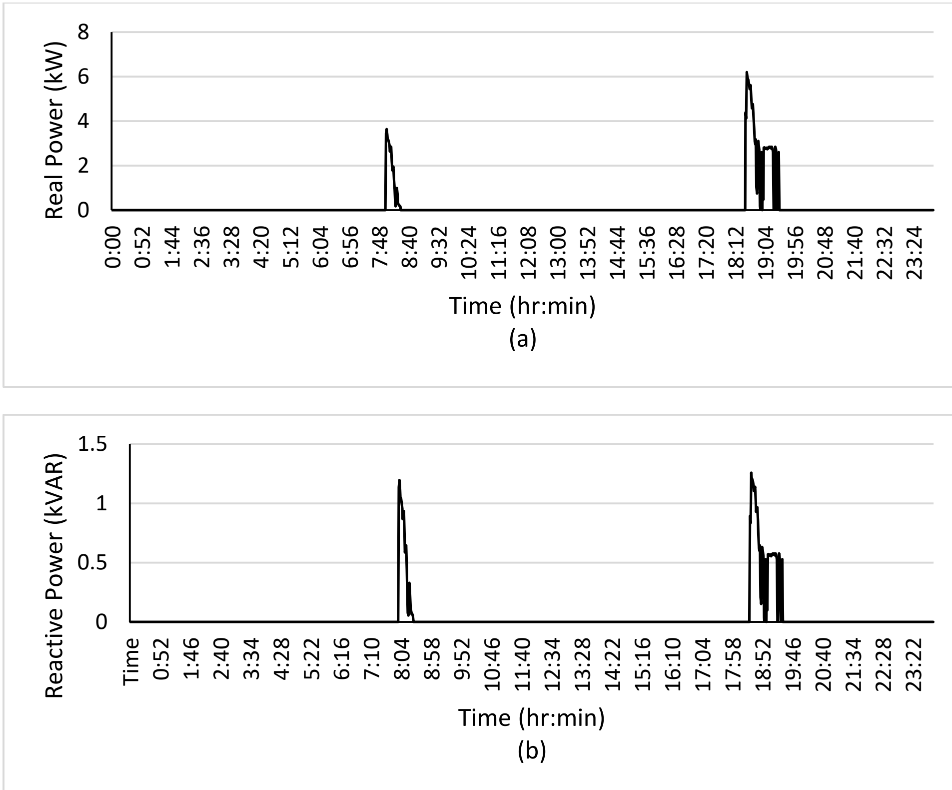


Figure 3.7. Oven load profile: (a) real power; (b) reactive power.

3.1.8 Various Loads Model

The Office of Energy Efficiency & Renewable Energy (EERE) publishes hourly load profiles for commercial and residential building varying by location [16]. The data set for Fulton County, Georgia was used to model the various loads in the test house. The loads for general interior lighting and interior equipment were used, with each category varying by the hour. This load is shown in Figure 3.8.

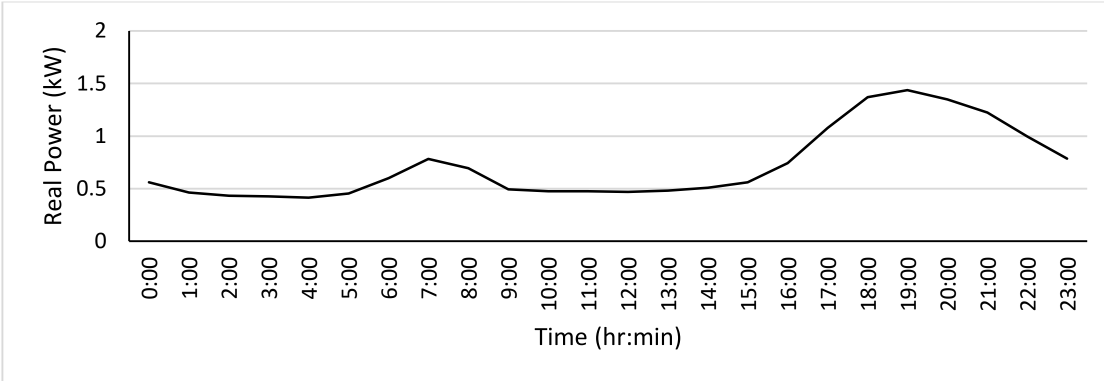


Figure 3.8. Various Loads load profile.

3.2 Battery Energy Storage System Model

To simulate a BESS used with a residential house, an equivalent circuit for an electric battery and switching inverter are needed. For the battery the ideal model was selected as an equivalent circuit, allowing the internal resistance and overvoltage impedance of the battery to be disregarded to simplify the model [13]. Since the power grid operation frequency is much lower than the switching frequency of commercial inverters a low-frequency equivalent circuit can be used, allowing for much faster simulation times [15]. Additionally, the BESS was assumed to have a constant discharge current over the course of use. For a battery with a constant discharge rate the SOC of the battery can be defined using the capacity C_i and discharge capacity C_{Di}, where the discharge capacity is defined with the rate of discharge I_i and time t [2].

$$SOC = 1 - \frac{C_{Di}}{C_i} \tag{3.1}$$

$$C_{di} = I_i t \tag{3.2}$$

Two mature and commercially available technologies for residential BESS are lead-acid and lithium ion batteries [2], [23]. In order to simulate the impact of both battery technologies both a lead-acid and lithium ion BESS were modeled. Given that various TOU pricing models are dependent on the time of demand and/or the maximum demand, each battery type will be simulated over both a 4-hour discharge and a 5-hour discharge. The specifics of the TOU pricing models will be discussed in chapter 4, and the specifics of the different simulations will be discussed in chapter 5.

In order to model the power draw when the BESS is charging it is represented by an active and reactive load, connected when the BESS is charging. To minimize the impact on the total house demand each BESS is charged over 6 hours, from midnight to 6:00 am when demand is lowest. For discharge, the BESS is modeled with a reduction in the house load by an amount equal to its discharge capacity.

3.2.1 Lead-Acid Battery Model

For the lead-acid batteries, the Outback EnergyCell 200RE was used. Since the capacity of an EnergyCell 200RE depends on the length of discharge, the power supplied must be determined separately for each case. The parameters for the EnergyCell 200RE are shown in Table 3.1 [24], [25].

Table 3.1. Outback EnergyCell 200RE specifications [24], [25].

Cost	$436	$436
Discharge Time	4 hours	5 hours
Capacity	1.675 kWh	1.746 kWh
Power	418.8 W	349.2 W
Efficiency	Not Listed	Not Listed
Voltage	12 V	12 V
Discharge Current	34.9 A	29.1 A
Charge Current	30 A	30 A

Outback recommends that the EnergyCell batteries not be discharged to lower than 50% depth of discharge (DOD) in order to lengthen the battery lifetime [24]. Therefore, when operating from a DOD of 0% - 50% the EnergyCell 200RE can supply 209.4 W over a 4-hour discharge and 174.6 W over a 5-hour discharge when discharging at a constant rate.

The maximum specified capacity for an EnergyCell 200RE is 200 Amp-hours over a 100-hour discharge, which results in a 2400 kWh capacity. In order to model the EnergyCell 200RE charging, this 2400 kWh capacity was assumed to be the required charge level. Since the EnergyCell 200RE is only discharged to 50% DOD when used, the starting point for charging was assumed to be 50% SOC. Thus the load was set to 200 W over the course of the 6-hour charging period from midnight to 6:00 am in order to return to a 100% SOC.

3.2.2 Lithium Ion Battery Model

For the lithium ion batteries, the Tesla Powerwall was used. The parameters for the Powerwall are shown in Table 3.2 [26].

Table 3.2. Tesla Powerwall specifications [26].

Cost	$3,000
Capacity	6.4 kWh
Power	3.3 kW
Efficiency	92%
Voltage	350 - 450 V
Discharge Current	9.5 A
Charge Current	Not Listed

Unlike the EnergyCell 200RE above, the Powerwall is capable of reaching a DOD of 100%, allowing full use of the 6.4 kWh for daily cycle applications [26]. Therefore, it can supply 1.6 kW over a 4-hour discharge and 1.28 kW over a 5-hour discharge when discharging at a constant rate. The Powerwall is specified to operate at 92% efficiency, which given 6.4 kWh available for use and 100% depth of discharge results in a 6.92

kWh charged capacity. In order to model the Powerwall charging, the load was set to 1.153 kW over the course of the 6-hour charging period from midnight to 6:00 am.

3.3 Test House System Model

In order to measure the power draw of the test house model and BESS model, a distribution level test house system was developed. This test house system includes the Test House and two neighboring houses, the Second House and the Third House. Each house is set up the same, containing the seven household appliances and various loads as described in section 3.1, with the same load profiles.

The connecting distribution grid includes a 13.8 kV slack generator, a 13.8 kV transmission line between the slack generator and the first pole, a 13.8 kV transmission line between the first pole and the second pole, two residential transformers on Pole 1 feeding the Test House and the Second House, and one residential transformer on Pole 2 feeding the Third House. Each residential transformer is a 15 kVA, 7.9/0.24 kV, single phase, center tapped secondary transformer. This system is shown in Figure 5.1, with the Test House labeled THOUSE, the Second House labeled 2HOUSE, and the Third House labeled 3HOUSE.

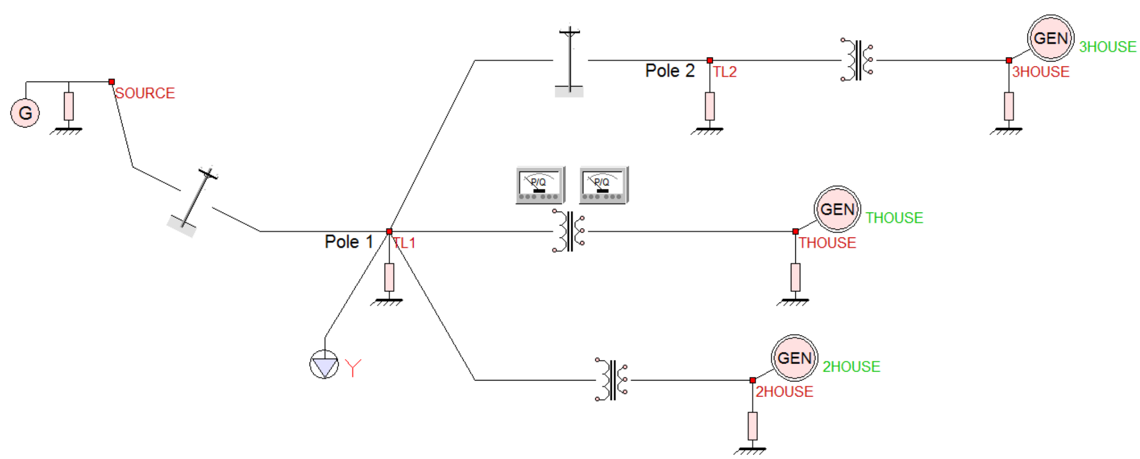


Figure 3.9. Distribution level grid for test house sytem.

CHAPTER 4

ECONOMIC MODEL

In order to quantify the impact of a BESS on a residence the total project valuation of the addition of a BESS must be determined. The following chapter presents the valuation methodology and TOU pricing used to determine the present cost of installing a residential BESS in sections 4.1 and 4.2, respectively.

4.1 Present Cost Valuation

In order to quantify the cost benefit of adding a BESS to a residential house, the yearly savings in electricity costs over the lifetime of the BESS must be converted to a present value and compare to the initial cost of the system. In order to determine the present value P of some future value F that is *n* years in the future, equation (4.1) is used where *i* is the discount rate.

$$\mathrm{P} = \mathrm{F} * (1 + i)^{-n} \tag{4.1}$$

When the future cost is not a one-time cost and reoccurs every year, equation (4.2) is used to determine present value, where U is the uniform annual payments and *n* becomes the total number of years.

$$\mathrm{P} = \mathrm{U} * \frac{[(1+i)^{n} - 1]}{i(1+i)^{n}} \tag{4.2}$$

When the future cost is a recurring annual cost that changes yearly a geometric series, as shown in equation (4.3), is used to determine the present cost where A is the initial annual payment, and *e* is the annual escalation rate of the future costs.

$$\mathrm{P} = \mathrm{A} * \frac{[(1+i)^{n} - (1+e)^{n}]}{(i-e)*(1+i)^{n}} \tag{4.3}$$

Since the cost of electricity varies yearly, equation 4.3 was used to determine the present value of electricity costs. A is the initial yearly energy cost, *i* is the homeowner's discount rate, *e* is the yearly increase in electricity costs, and *n* is the lifetime of the BESS.

The Energy Information Administration (EIA) estimates the increase in yearly electricity prices [18]. Since the cost of electricity fluctuates year to year, the assumed value for the escalation rate *e* was the average of the previous three years, since 2014. This value was 1.72% [18]. There has been a model developed to estimate the discount rate for individuals when purchasing energy consuming appliances [19]. This model predicts a discount rate between 5.1% and 89% depending on the annual income of the individual in question. For this valuation at discount rate of 8.9% was used, the rate modeled for an individual with an income of $35,00 - $50,00 annually [19].

When adding a BESS to a residence, the present value cost of the project valuation can be determined by adding the present worth of the total energy costs over the lifetime of the BESS to the initial purchase cost of the BESS. This can be compared to the total present value of the energy costs of the residence without a battery to determine the value of adding a BESS to the residence.

4.2 Time-Of-Use Pricing

Georgia Power operates several rate plans utilizing TOU pricing for their consumers, specifically the Standard Service Plan, the Nights and Weekends plan, and the Smart Usage Rate plan [20], [21], [22]. The prices for these three rate planes are summarized in Table 4.1 for the Standard Service Plan, Table 4.2 for the Nights and Weekends plan, and Table 4.3 for the Smart Usage Rate plan.

Table 4.1. Standard Service Plan pricing [20].

Season	Winter Months	Summer Months
First 650 kWh	5.6582¢ per kWh	5.6582¢ per kWh
Next 350 kWh	4.8533¢ per kWh	9.3983¢ per kWh
Over 1000 kWh	4.7641¢ per kWh	9.7273¢ per kWh

Table 4.2. Nights and Weekends plan pricing [21].

On-Peak kWh	20.3217¢ per kWh
Off-Peak kWh	4.6430¢ per kWh

Table 4.3. Smart Usage Rate plan pricing [22].

On-Peak kWh	9.6052¢ per kWh
Off-Peak kWh	0.9754¢ per kWh
Demand Charge	$6.53¢ per kWh

Georgia Power defines winter months as October – May and summer months as June – September [20]. On-Peak hours are defined as 2:00 pm – 7:00 pm Monday through Friday during summer months. These days exclude the national holidays of Independence Day and Labor Day [21], [22]. For the Smart Usage Rate plan, demand charge is defined as the highest 30-minute kW measurement during the month [22].

Please note that these prices only represent the customer's energy charges, and not any basic service charges, cost recovery charges, or any other fee added to the customer's bill. Therefore, any cost calculated using only these prices will not be indicative of the customer's total electricity bill, only of the energy cost for that time period.

CHAPTER 5

SOLUTIONS

The following chapter presents the execution and results of the simulations of the daily power draw for a typical residence test case and a test case with a BESS in sections 5.1 and 5.2 respectively. These results are then applied to standard TOU pricing plans in section 5.3 to determine project valuation for the addition of a residential BESS.

5.1 Initial Test Case Simulation

The initial test case simulation was for the test house with no BESS installed. This includes only the loads as described in section 3.1 measured on a test system as described in section 3.2. The resulting load profile is shown in Figure 5.1 below.

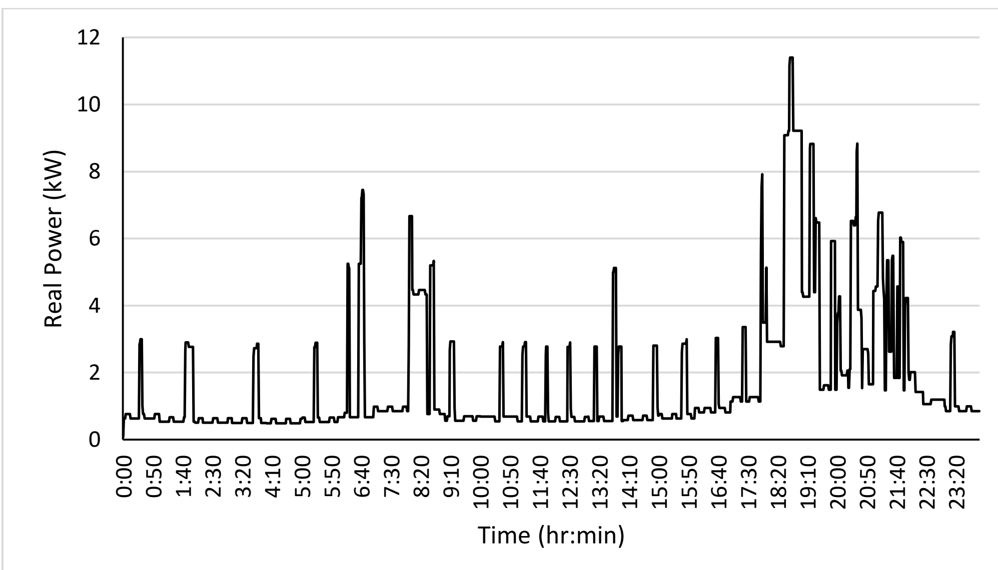


Figure 5.1. Demand without battery.

The load remains consistent throughout the day, with only a few spikes during the morning around breakfast time, until the evening, around 6:00 pm. At this time the load increases due to appliance usage and the increase in lighting and miscellaneous loads, until later when it tapers off again.

5.2 Battery Energy Storage System Test Case Simulations

In order to measure the effect of a BESS on the test house a BESS, modeled as described in section 3.2, was added to the test house. This includes separately modeling both a lead-acid BESS and lithium ion BESS. There was no BESS added to the Second House or the Third House during these simulations.

Since the TOU pricing plans described in section 4.2 vary based on both time and peak demand, each BESS was simulated with two different discharge times. The first method was to discharge the BESS during times of peak demand, in order to reduce the peak load of the test house. Thus the BESS were discharged over 4 hours from 6:00 pm – 10:00 pm. The second method was to discharge the BESS during on-peak hours as defined by Georgia Power. Thus the BESS were discharge over 5 hours from 2:00 pm – 7:00 pm.

5.2.1 Lead-Acid Battery Simulations

Using the Outback EnergyCell 200RE described in section 3.2 as the lead-acid BESS, the resulting load profile for both a peak load reduction and on-peak hours load reduction are shown in Figure 5.2 and 5.3 respectively.

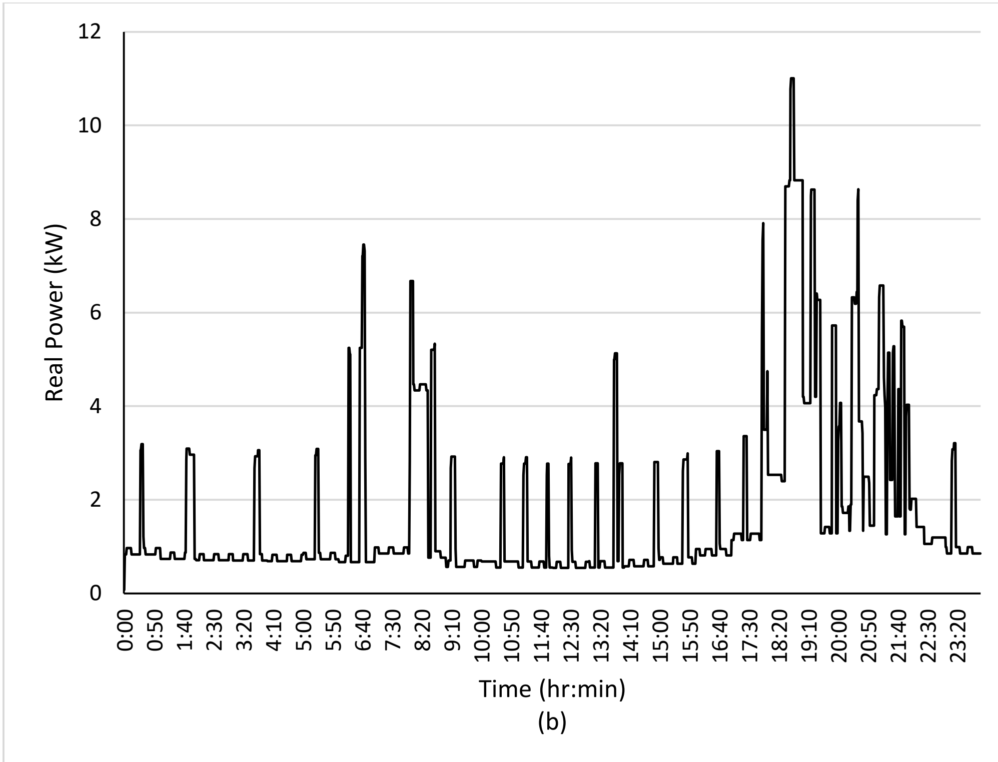


Figure 5.2. Demand with lead-acid battery for peak demand reduction.

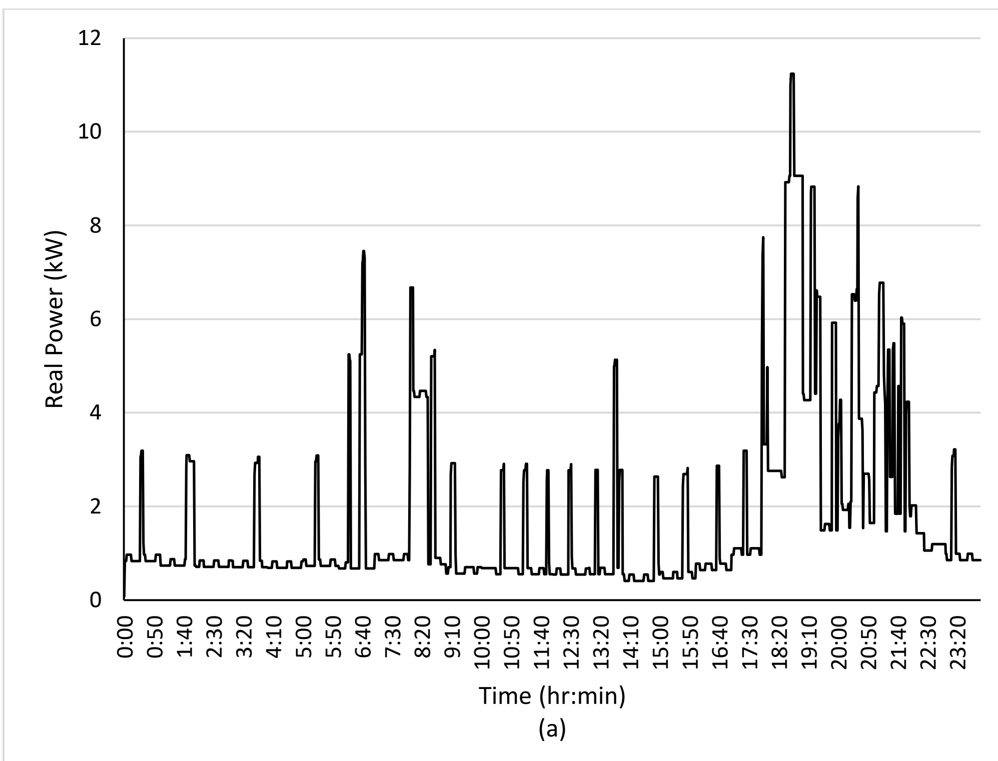


Figure 5.3. Demand with lead-acid battery for on-peak hours load reduction.

This results in a slight reduction over the discharge time for both methodologies, as the EnergyCell 200RE does not have an overly large capacity. Both methodologies also have an increased load during the charging time in the morning.

5.2.2 Lithium Ion Battery Simulations

Using the Tesla Powerwall described in section 3.2 as the lithium ion BESS, the resulting load profile for both a peak load reduction and on-peak hours load reduction are shown in Figure 5.4 and 5.5 respectively.

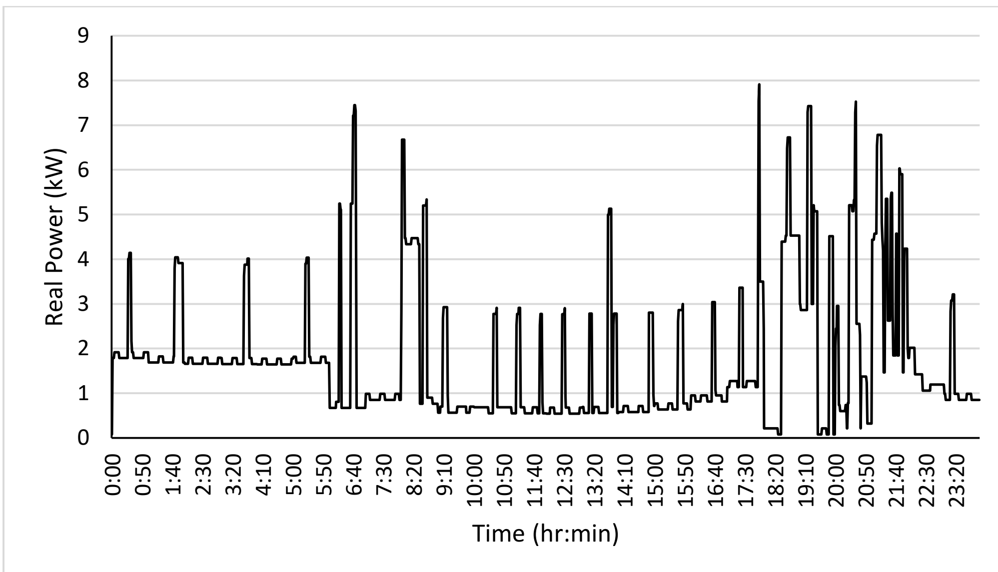


Figure 5.4. Demand with lithium ion battery for peak demand reduction.

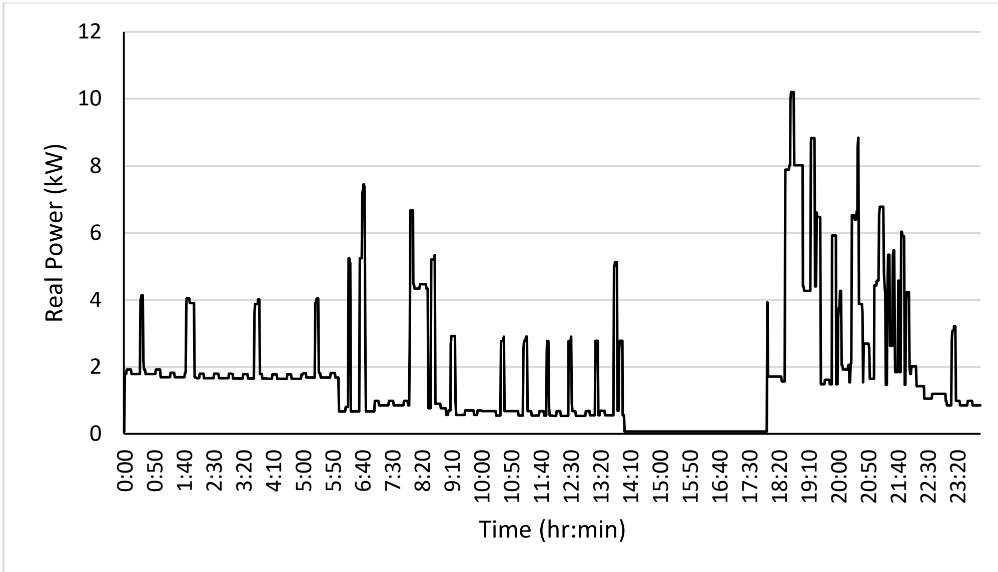


Figure 5.5. Demand with lithium ion battery for on-peak hours load reduction.

This results in a great reduction over the discharge time for both methodologies, as the Powerwall has a much larger capacity than the EnergyCell 200RE. For the on-peak hours' load reduction this almost completely eliminates the test house load. Both methodologies also have a greatly increased load during the charging time in the morning.

5.3 Time-of-Use Pricing Project Valuations

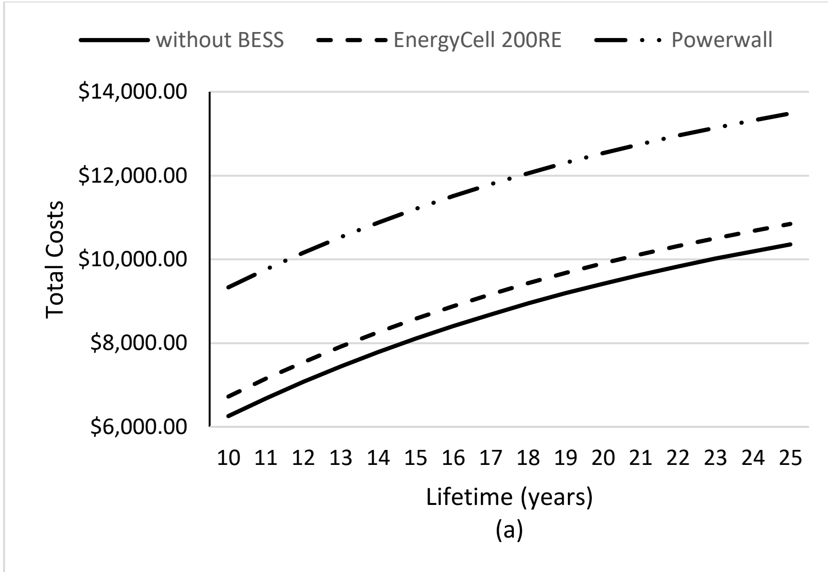
Each TOU pricing plan shown in section 4.2 varies electricity cost based on billing season. For summer months (June – September) the Standard Service Plan has higher rates, and both the Nights and Weekends and Smart Usage Rate plans have on-peak hours, excluding weekends and two federal holidays. For the Standard Service Plan this totals 122 summer days where summer rates are active. For the other two plans this totals 84 summer days where on-peak hour prices are active and 38 summer days where they are not. During winter months (October – May) the Standard Service Plan has lower rates and the Nights and Weekends and Smart Usage Rate plans do not have on-peak hours. This totals 243 winter days where neither summer rates nor on-peak hours are active. Annual costs for each pricing plan are shown in Table 5.1, based on the specific BESS simulation.

Table 5.1. TOU pricing plan annual simulated costs.

	Standard Service Plan	Nights and Weekends	Smart Usage Rate
No BESS Installed	$958.17	$882.67	$988.51
Lead-Acid BESS Peak Load Reduction	$962.86	$881.00	$925.06
Lead-Acid BESS On-Peak Hours Load Reduction	$966.36	$877.44	$958.18
Lithium Ion BESS Peak Load Reduction	$969.39	$843.06	$596.47
Lithium Ion BESS On-Peak Hours Load Reduction	$983.71	$824.75	$856.00

The Outback EnergyCell 200RE is rated to stay at 80% maximum capacity for 1800 cycles when discharged to 50% regularly [23]. As noted above there are 84 days annually where the BESS would need to be cycled, so the EnergyCell 200RE can be expected to last up to 21 years. The Tesla Powerwall comes with a 10-year warranty [26]. Therefore, it’s expected lifetime can be assumed to be at least 10 years. Using these times as estimates, the methodology shown in section 4.1, and the costs listed in section 4.2 the present value costs of installing each BESS can be determined.

The project valuations using the Standard Service Plan are shown in Figure 5.6.



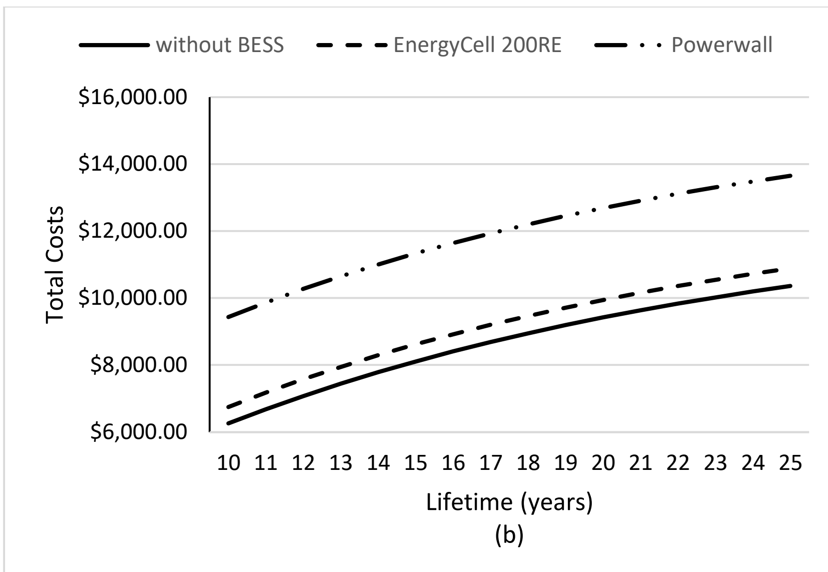
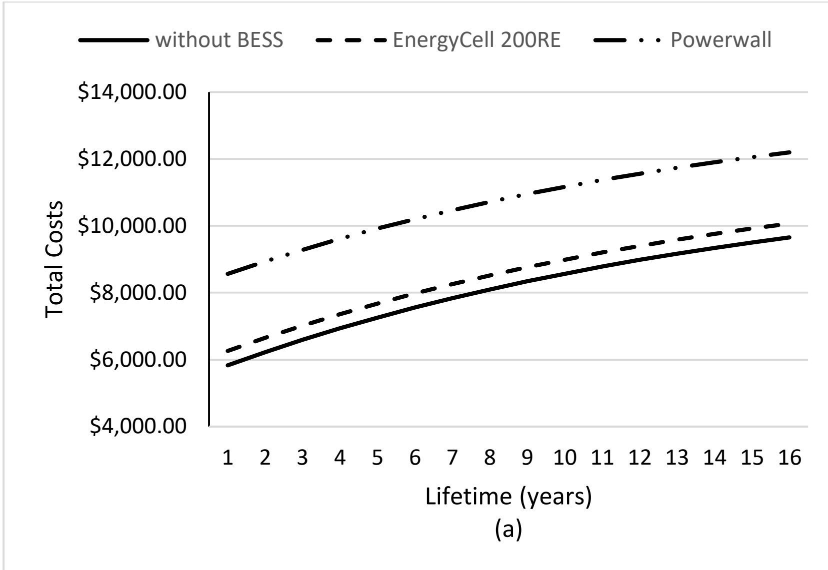


Figure 5.6. Standard Service Plan project valuations: (a) peak load reduction; (b) on-peak hours load reduction.

The Standard Service Plan separates the daily load of a residence into three tiers, one for the first 650 kWh, next 350 kWh, and anything over 1000 kWh. Thus, the only incentive is to reduce the residence's total daily load. As shown the addition of a BESS only increases the total cost for the homeowner over the entire expected lifetime, for both the EnergyCell 200RE and the Powerwall.

The project valuations using the Nights and Weekends pricing plan are shown in Figure 5.7.



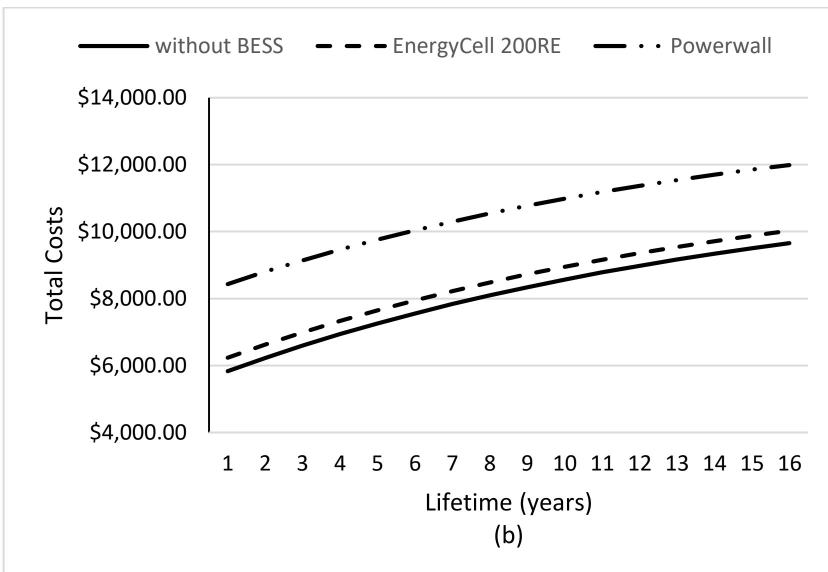
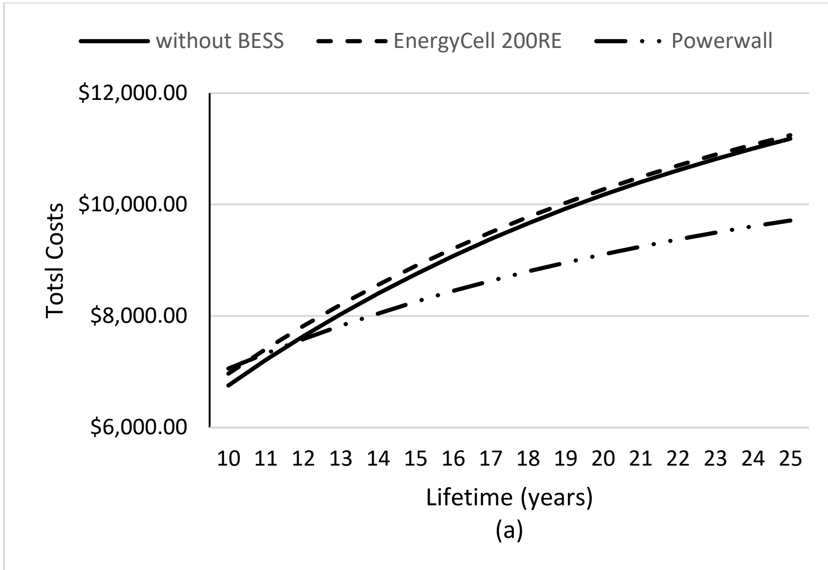


Figure 5.7. Nights and Weekends project valuations: (a) peak load reduction; (b) on-peak hours load reduction.

The Nights and Weekends plan separates the daily load of a residence into on-peak and off-peak hours. This incentivizes the homeowner to shift demand to off-peak hours. As shown however, these savings are not enough to offset the initial cost of the battery, for both the EnergyCell 200RE and the Powerwall.

The project valuations for the Smart Usage Rate pricing plan are shown in Figure 5.8.



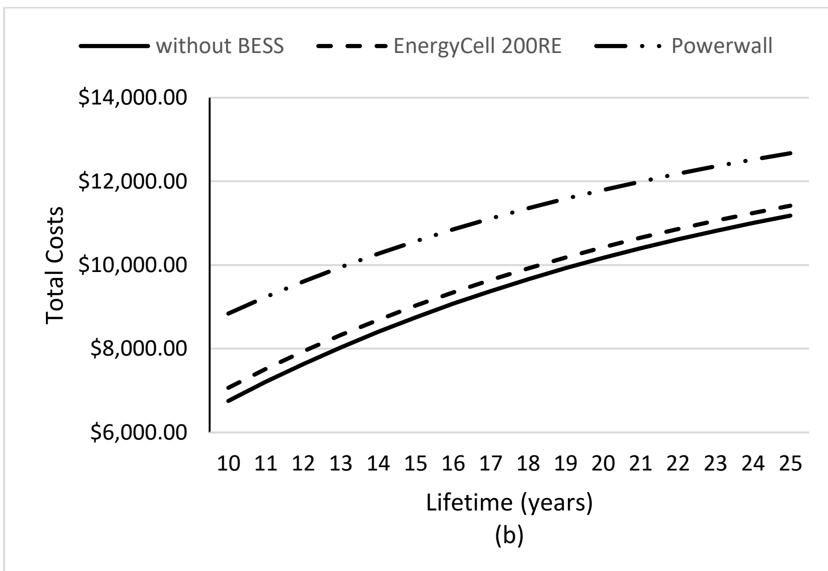


Figure 5.8. Smart Usage Rate project valuations: (a) peak load reduction; (b) on-peak hours load reduction.

The Smart Usage Rate also separates the daily load of a residence into on-peak and off-peak hours, but additionally has a demand charge for the maximum kW measured that month. This incentivizes the homeowner both to shift demand to off-peak hours and reduce peak demand. As shown, using a BESS to reduce peak load provides enough energy savings to offset the cost of either the EnergyCell 200RE or the Powerwall. Using a BESS to reduce on-peak hours' load does not offset the cost of either the EnergyCell 200RE or the Powerwall.

In order for a residential BESS to be beneficial to a homeowner, it must pay for the purchase cost of the battery through energy cost savings. The only simulations to reach minimum payback within the lifetime of the BESS simulated were by reducing peak load using the Smart Usage Rate TOU pricing plan for both the EnergyCell 200RE and the Powerwall. The EnergyCell 200RE reached minimum payback after 10 years, and the Powerwall reached minimum payback after 12 years.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

TOU pricing are a DR program put into place by electric utility providers in order to lower peak loads as well as shift loads away for peak hours, reducing the strain on the electric power grid. BESS provide a way for homeowners to take advantage of these pricing plans by shifting their household loads with little impact on their daily lives. This provides an opportunity for homeowners to reduce their electric bill while benefiting the local electric utility provider. This thesis provides a method and results of simulating these benefits for the homeowner. The rest of this chapter reviews the research done to provide a project valuations and to quantify the cost benefit of installing a residential BESS.

In order to determine these project valuations two models were developed. First physical models were developed for a typical Atlanta house, both a lead-acid and lithium ion BESS, and a distribution network connecting this house. The test house model was based on household appliance load profiles, and the average electricity consumption for lighting and general interior loads of Atlanta houses. Specification sheets provided the expected capacity and output of the BESS. These models were used to create daily load profiles for the test house with and without BESS installed and provided detailed kWh simulations. Second an economic model was developed, including a method for present value determination and TOU pricing, that was used to show the economic impact of peak shifting with these BESS. Adding the simulated present value energy costs to the purchase coast of the BESS provides a total present value of installing the BESS. This is compared to the present value energy costs of the test house without a BESS to determine the benefit of installation.

As shown, the only simulation where a system reaches minimum payback within its lifetime is using either the EnergyCell 200RE or the Powerwall battery with the Smart Usage Rate pricing plan while aiming to reduce peak demand. The EnergyCell 200RE reaches minimum payback at 11 years, which is 9 years past the end of the battery's warranty, while the Powerwall reaches minimum payback at 12 years, which is only 2 years past the end of its warranty. Additionally, the Powerwall system provides a much larger reduction in costs as the lifetime of the battery progresses. While the Nights and Weekends pricing plan does incentivize shifting loads away from peak hours, it is not enough to cover the cost of purchasing a BESS. It is the focus on peak demand in the Smart Usage Rate that provides the benefit necessary to cover this cost. Thus the best recommendation for a homeowner is to install a Powerwall, or other lithium ion based BESS, programed to reduce peak loads and switch to the Smart Usage Rate, or similar, pricing plan.

Future work regarding these topics involves expanding the physical model for the test house and BESS. This can include different BESS technologies, as only two were examined here, and the expansion of the test house model to include PV systems, electric vehicles, or any additional appliances. Finally, another avenue of research would be to adapt this methodology to simulate commercial or industrial locations. This would provide the same cost benefit estimation on a much larger level.

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